Bio-Inspired and Life-Inspired Sensors

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3.1 Introduction

Living beings have always inspired the imagination of inventors and scientists throughout history. According to Greek mythology, Daedalus invented a pair of wings made out of waxed feathers so that he and his son Icarus could escape from the labyrinth of Crete. They succeeded, but Icarus flew so close to the sun that the wax melted and his wings dismantled, with tragic consequences. In renaissance Italy, Leonardo da Vinci invented flying machines and submarines inspired by birds and fish more than 500 years ago, but his inventions never came into real practice. These attempts failed not because they were fundamentally flawed, but mainly because technology at the time was far too immature for any realistic implementation of such projects.

What are the distinctive features of biological systems that we would like to incorporate in our man-made systems? Here is a partial list:

• Resilience. The ability to continue functioning even when the system has suffered damage (fault-tolerance).
• Healing. The ability to recover from damage and return the system to a state similar, if not identical, to the state it was before damage occurred.
• Low power. Living organisms are extremely efficient in transforming energy (food) into growth and behaviors.
• Autonomy. Plants and animals do not need external control to survive. Their behaviors are either innate, or learned from interactions with their environment.
• Evolution, adaptation, and learning. Biological organisms have these mechanisms that allow them to adapt, up to a certain extent, to changes in their environment.
• Intelligence. The ability to perceive the environment and interpret it to produce behaviors in response to possible outcomes.
The remarkable increase in computational power and, more recently, advances in the architecture and size of field-programmable logic devices (FPLDs) have made it possible to build devices inspired by mechanisms found in nature. Artificial neural networks (ANN) and evolutionary algorithms (EA) are many examples of bio-inspired techniques that have been successfully developed and incorporated in commercial systems. In this chapter, we will discuss fundamentals of bio-inspired sensors and give some examples of their applications.

With today’s technology it is possible to implement a complex system on a single chip with capabilities listed previously. The possibility is enhanced due to integration of the wireless communication systems and complex networking capabilities on that chip. These new types of systems are feasible and affordable for applications that require miniaturization, high performance, low-power dissipation, and distant communications. There are many advanced devices available to transmit and process measurement information from mobile objects, from inaccessible places, or remote devices and machines. This prompts stimulus for development of much rigorous and more complex niche and application-specific systems. Most of these application-specific systems contain integrated embedded microprocessor circuits that have included intelligence, augmented reality, and wearable or implanted components. It is worth mentioning that they are and must be extensively supported by a range of appropriate software.

### 3.2 Bio-Inspired Systems

For the purpose of studying life looking for inspiration, living organisms can be described at four fundamental structural levels, as in Figure 3.1. The features at one level of the hierarchy emerge from the interaction of elements at lower levels. Understanding life in any depth requires knowledge of all four levels shown in Figure 3.1. A forth level can be suggested in which organisms from the same or different species interact with each other in the form of populations and ecosystems, respectively. In current research, hardware systems are used to study the organ, system, and organism levels. Cellular and population levels are studied mainly with the software systems.

![Hierarchical structures of multicellular organisms. (Authors’ artwork incorporating Microsoft clip arts.)](image-url)
Even though elements from every level in Figure 3.1 are very different in size and behavior, there are certain features common to all:

- Interaction of simple components that generates complex emergent behaviors
- Asynchronous interaction: As most interactions are event-driven, there is no explicit synchronization
- High level of redundancy

Current research in bio-inspired systems focuses in one, or more, of these features. In order to exploit these features, a commonly studied but very fundamental area is the bio-inspired semiconductor sensors and will be discussed in this chapter in detail.

3.3 Life-Inspired Systems

The paradigm of the life-inspired systems originates from the observations with the aim that the micro-electronic-based systems should have characteristics resembling the characteristics of individual life organisms or organized populations.

Engineers and scientists aim for autonomous, self-contained, robust, self-organizing, self-adapting, self-regulating dynamic evolutionary systems that resemble real organisms. The products should be composed of autonomous systems made from diverse subsystems, but each of which has its own functionality to be integrated with the other subsystems and the central organizer just like the brain or nervous system in living organisms. The aim is to come up with systems that do not limit themselves to the basic functions of collecting, transmitting, storing, processing, and presenting information in relation to some external systems, but in addition they are able to solve complex problems, make and implement difficult decisions, learn, discover new ideas, and evolve.

To efficiently develop the new systems closely resembling intelligent life organisms, new system architecture concepts and design methods and tools are developed. Challenges in biologically and life-inspired systems created a new field termed as bio-inspired engineering. This new discipline applies biological principles to develop new engineering solutions for industry, medicine, environment, and many other fields that have not been previously investigated. The emergence of this discipline is the culmination of the unification of the life sciences with engineering and physical sciences. Hence, bio-inspired engineering involves deep exploration into the living cells, tissues, and organisms that can build, control, regenerate, recycle, and adapt to their environment.

A well-studied area in bio-inspired and life-inspired systems is artificial intelligence (AI). Many AI techniques have been developed and applied using computer-based technologies. Various computational models and knowledge-based systems have been applied in industrial, economic, and many other areas for the purpose of automated reasoning, learning, and problem-solving. There are thousands of publications on AI. As an example, an advanced study on AI is web intelligence (WI). Since the web is the largest network, the application of AI on this large scale is demanding and challenging. Studies such as WI brain informatics (BI) are leading to profound advances in the analysis and understanding of data, information, knowledge, and wisdom, as well as their interrelationship, organization, and creation process. Research and development in WI is making it possible to develop human-level WI [1–3].

3.4 Semiconductor Sensors

Since the early 1970s, silicon technology has been used to detect chemical changes such as hydrogen ions, pH levels, chemical substances, and odor detection. Since then many more sophisticated sensors have been developed based on complementary metal oxide semiconductor (CMOS), ion-sensitive field effect transistor (ISFET), metal oxide semiconductor field effect transistor (MOSFET), and other similar technologies. Many advanced types of semiconductor sensors are available, some of which are known as chemical field effect transistors (CHEMFETs) and enzyme field effect transistors (ENFETs).
for sensing various analytes, elements such as potassium, sodium, and complex chemical structures such as glucose in blood and urea.

Chemical sensors have been leading to semiconductor-based devices to lead to bio-inspired sensors. Figure 3.2 illustrates an example of semiconductor-based optical chemical sensor. The sensor consists of two chambers, one acting as a reference containing a reference concentration chemical and the other as the sensor. These chambers are illuminated by a common light-emitting diode (LED). The surfaces of chambers are metallized to improve internal reflectivity, and the bottom of chambers is covered by glass. One of the chambers has slots covered with a gas-permeable membrane. The slots allow the penetration of gas to be measured (e.g., CO₂) into the chamber. Wafers A and B form optical waveguides. The chamber filled with reagent is used to monitor the optical absorbency for comparison with that obtained from the reference chamber.

Another example semiconductor-based sensor is the ISFET sensor is illustrated in Figure 3.3. In this example, the sensor is chemical based, and the signals generated by the sensor are amplified and processed in the same chip.
In addition to simple single-chip chemical sensors, there are many complete systems that have extensive and complex information processing features all built on a single chip or in a single package. The implementation of complete systems on a chip (SoCs) or in a system in package (SiPs) enables development of new generation sensors in a diverse range of application [4–6]. Nowadays, the use of semiconductor technology in biomedical systems is an accepted norm and very common. One of the most advanced technologies is DNA sequencing where the DNA and variations in the DNA are used to trigger sensors in microchips and go further by taking the necessary actions to be followed.

3.5 Biomedical and Biological Sensors

Semiconductor-based sensors for biomedical and biological applications have been researched and developed extensively. They find many applications, including the following:

- Biopotential and electrophysiology determination
- Blood pressure measurements
- Blood flow measurements
- Body temperature measurements
- Body weight and composition measurements

Traditionally, biological detectors require human intervention in a laboratory environment. However, in recent years, automatic devices and robots have involved biological applications, such as detection of microorganisms and their concentration levels. For example, for the detection of microorganisms in air, three different common methods are as follows:

1. **Biochemical**, which detect a DNA sequence and protein that are unique to a bio-agent through its interaction with test modules
2. **Chemical**, for example, mass spectrometry, which works by breaking down a sample into its components such as amino acids and then comparing their weights with those of known bio-agents and other molecules
3. **Biological tissue-based systems**, in which a bio-agent or biotoxin affects live mammalian cells, causing them to undergo some measurable response

Some classes of biosensors rely on comparing the DNA taken from a microorganism with the DNA of a known agent [7–9]. In other classes, there are microfluidic devices, which contain capillary channels, valves, and chambers in a single chip. Once the microorganism is in the chip, their cells are cracked open ultrasonically. Then polymerase chain reaction (PCR) is applied by means of small thin film heaters.

Some semiconductor sensors apply either optical and fluorescent methods or magnetic methods, as illustrated in Figure 3.4. These devices comprise an array of wirelike magnetic field microsensors. These sensors are coated with single-stranded DNA probes specific for a gene from a bio-agent. Once a strand of bio-agent DNA in a sample binds with a probe, the resulting double strand binds a single magnetic microbead. When there are magnetic beads in the sensor, the resistance of sensor decreases in proportion to the number of microbeads.

Among many other methods, in one application multiple array biosensors are multiplexed and electrochemical detection is realized by using an electronically active substrate, which has been constructed with a standard CMOS technology.

Another commonly used method for biosensing is by the use of live tissues. Many toxins trigger measurable or differentiable reactions in living cells. Mammalian cells, such as heart cells, are cultured in a lab and then seeded into a cartridge containing a microelectrode array. When a biotoxin is introduced, the cells create voltages detectable in millivolts at the electrodes.
3.6 Biomimetic Sensors

Bar-Cohen [12,13] explains that organisms use numerous receptors (senses) to control every aspect of their life and functions. Due to millions of years of evolution, biological sensors became very effective for providing external and internal information to warn about dangerous conditions, sense locations, control growth, and functionality of organs. These near-perfect capabilities of biological sensors prompted scientists and engineers to make efforts to understand and mimic them as closely as possible.

Scientists and engineers are studying biological sensors to copy, adapt, and inspire new capabilities and apply them in diverse ranges. These studies require interdisciplinary collaboration of researchers from the fields of biology, materials science, mathematics, engineering, medicine, chemistry, and physics as well as involvement of social scientists [14–16].
3.7 Signal Processing

Bio-inspired sensors commonly come as microchips, and they largely generate analog signals. As in the case of all analog sensors, the signal processing requires analog-to-digital and digital-to-analog conversions, illustrated in Figure 3.5.

**FIGURE 3.5** A bio-inspired data acquisition and control array.
The system in Figure 3.5 comprises hardware and software elements. Each one of them can potentially be biologically inspired. The number of interesting mechanisms and behaviors that could be adapted from nature into man-made systems is vast; therefore, it is possible to apply bio-inspiration to any of the blocks.

The basic principles of sensors can be temperature variations in physical (dimensions, resistivity, capacitance, etc.) or chemical (phase, color, pH, etc.). Hence, the signal processing requires appropriate selection of techniques suitable to the nature of the signals as they can be inductive, capacitive, and resistive, or they can be current source or voltage source [21, 22]. In most cases the outputs of the sensors are not linear; therefore, extensive signal conditioning is required, such as the following:

- Linearization
- Impedance-matching circuitry
- Amplification
- Filtering
- Integration
- Differentiation
- Modulations

A typical example of signal processing requirements in biosensors is implantable medical devices, which require extreme low-power operation to avoid periodic replacement of batteries for long-term maintenance-free operation. For real-time monitoring of health condition, implantable medical devices also need to transmit the vital information outside of the human body for further diagnostics and processing. In an application, a data generator block takes the signal from sensors and transforms the signal into frequency-modulated digital pulses by employing relaxation oscillators. The next block such as the impulse generator converts the digital pulses into impulse signals for impulse-radio-based wireless telemetry.

AI is a commonly used technique for signal processing information from biosensors. For example, in an application a biosensor was simulated employing a feed-forward neural network with three layers and trained using a back-propagation (BP) algorithm [23]. Spectra generated from an optical phenolic biosensor at selected wavelengths were used as input data for an ANN. The network architecture of 5 inputs neurons, 21 hidden neurons, and 1 output neuron was found suitable for this application. The results had been compared with the information obtained from the operational biosensors.

A new trend in bio-inspired sensors is the use of field-programmable gate arrays (FPGAs) as they inherently offer greater flexibility in system configuration, application of AI, and flexibility in software development. In a study attempt has been made to replace microcircuits by FPGAs in portable biosensor devices [24]. In future technology electrochemical-based sensor chips such as pH, oxygen partial pressure, impedance, electrical potentials, and temperature can be used for the simultaneous in vitro measurement of metabolic, morphologic, and electrophysiological parameters. All these can be combined and the signals processed by using mixed signal electronic and local (point-of-care) analyses.

### 3.8 Bio-Inspired Sensors in Industry

Many of the interesting behaviors that can be found in nature are the result of nervous systems. Nervous systems include the senses and muscles to interact with the environment. Among species, vertebrates have evolved the most sophisticated nervous systems. Hence, they are a good source of inspiration for the investigation of bio-inspired systems.

The nervous system of mammals is made out of neurons with different functions according to where they are located in the sensory–motor cycle. In its simplest form, the sensory–motor cycle comprises three functional levels: the peripheral nervous system (PNS) that perceives and interacts with the environment, the spinal cord that transmits electrochemical signals, and the brain that receives signals generated by
sensory cells, processes them, and produces signals to control motor cells in the PNS. These three levels can be associated with the main components of a conventional control system, as shown in Figure 3.6.

Figure 3.6 suggests that in a first approximation, conventional control systems already have the hardware needed to implement bio-inspired systems. Bio-inspiration may apply to the way elements are interconnected and how software deals with sensor information to produce control signals. Good examples of this approach can be found in distributed control systems where intelligent sensors and actuators take low-level fast decisions at node-level while transmitting information to a central computer for high-level coordination. Properties like redundancy, event-driven processing, and fault-tolerance can be incorporated using additional hardware or software.

To achieve fault-tolerance, researchers are studying artificial immune systems (AIS) [25]. By using concepts like “the self” and “antigens,” systems are given the ability to recognize unexpected states (antigens) that do not belong in an expected state set (the self) and apply corrective measures to return the system to a “healthy” state.

### 3.8.1 Bio-Inspired Sensors in Control Systems

Process control is a typical area where bio-inspired systems find applications. In modern control practices, it is ever more frequent to find what are called “intelligent instruments.” These devices usually incorporate transducers, conditioners, analog-to-digital converters (ADCs), and a small local computer that can perform simple signal preprocessing and control. Information is transmitted from intelligent instruments to central computers using industrial buses and communication protocols. Figure 3.7 shows a typical control system that incorporates intelligent instrumentation.

Actuators are typical examples of bio-inspired systems [26,27]. They are essential elements within mechatronic systems due to their important role in motion control systems, and hence there is a need to develop new trend of actuators that can be inspired from biological actuation systems in nature and can be associated with different levels of control. Making intelligent devices by biologically inspired modern
actuators and artificial muscles can create a new reality with greater potential in comparison to conventional techniques. Electroactive polymers (EAPs) are a good example of materials that find usage as bio-inspired motion systems in industrial applications. EAP actuators are electrically responsive materials that have common characteristics with natural muscles and hence are suitable for “artificial muscles” in biomimetic motion applications. EAP materials can be activated either by electrically induced transport of ions or by electrostatic forces. EAPs are finding numerous industrial applications.

In one study, algorithms for bio-inspired tracking systems have been developed as the control algorithm for sensor-mediated chemical plume tracking in a turbulent flow environment. This study focused on development of a signal processing strategy capable of replicating behavioral responses of actively tracking strategies of blue crabs to chemical stimuli. The geometric arrangement of the sensor array is inspired by the location of blue crab sensor populations. Upstream motion is induced by a binary response to suprathreshold spikes of concentration, and cross-stream steering is controlled by contrast between bilaterally separated sensors [28].

References